Numerical Simulation of Temperature Distribution in A Tri-Cycle Engine Piston

Alabi Ismaila Olanrewaju, Olaiya Kamorudeen Adesina, Kareem Mutiu Olalekan

Abstract: Pistons as one of the most complex components among all automotives and other industry field components are designed to withstand damage caused due to extreme heat and pressure of combustion process. Many of experimental studies regarding the internal combustion engines process have been carried out, but few had only focused on the numerical studies like stress distribution, thermal and heat transfer analysis. This present study focuses on a 3-D transient state temperature distribution analysis on a gasoline piston model of a tri-cycle. Mathematical model was formulated, solved and simulated using a Finite Element Method (FEM) in-built in the COMSOL Multiphysics software 4.3a to determine the temperature distribution and gradient of the piston model ranging from 523K – 673K. The parameters used for the simulation were liquid (Gasoline), Gases (Air) and Aluminium alloy UNSA96061 (Piston). The Completed mesh tetrahedral consists of 86225 elements and the number of degrees of freedom solved for were 18553 in 367 s (6 minutes, 7 seconds) in the mesh optimization. It was discovered from the results obtained that the temperature in the combustion chamber of the tricycle engine varies with respect to time, along the piston.The transient analysis from the time dependent solver revealed that the temperature of the piston at the TDC (Top Dead Centre) in the first power stroke is higher compared to the subsequent power strokes, which is an indication that more heat was transfer at subsequent power strokes. Probable recommendations were later made.

Keywords: Tri-cycle, Piston, Aluminium alloy, Temperature distribution, Comsol.

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1 INTRODUCTION

Automobile components are in great demand these days as a result \of increased use of automobiles. The increased demand is due to improved performance and reduced cost of these components. R&D and testing engineers should develop critical components in shortest possible time to minimize launch time for new products. This necessitates understanding of new technologies and quick absorption in the development of new products [1].

The Internal Combustion (IC) engines had undergone significant advancements since their introduction in the early 16th century, and the latest trend is to make them greener. The latest trend in the IC engine industry is to develop power plants with higher efficiency and to make them running on alternative fuels to meet modern emission norms. There are different IC engine configurations used to generate mechanical output from chemical energy, namely reciprocating engines (single and double piston) and rotary engines. In general, a double piston engine delivers more power than a single piston engine for the same configuration [2].

Thus, engine pistons are one of the most complex components among all automotives and other industry field components [3]. A piston as a component of reciprocating IC- engines [4], reciprocating pumps, gas compressors and pneumatic cylinders, is the moving component that is contained by a cylinder. In an Internal Combustion (IC) engine, it is acted upon by the pressure of the expanding combustion gases in the combustion chamber and the motion is transmitted through the piston-connecting rod assembly to the crankshaft [5]. The temperature of a particular engine determines the performance of the engine.

However, the design/analysis of the piston is based on structural and thermal considerations [6]. Thus, in order to have full understanding of phenomenon of heat flow through the piston and liner, the temperature distribution within the piston and liner will come handy for designers while calculating the fatigue strength, thermal stresses and achieving higher output [7]. Invariably, piston as one of the most critical components of an engine must be designed to withstand the damages caused due to extreme heat and pressure of combustion processes. The value of stress that caused the damages can be determined by using FEA [8].

A finite element analysis (FEA) is a way of getting numerical solution to a specific problem. It neither produces a formula as a solution, nor does it solve class of problems. Also, the solution is approximate unless the problem is simple that a convenient exact formula is already available. It is used in solving field quantities such as stress analysis (stress field), thermal analysis (Temperature Field/Heat flux), fluid flow (Stream function/velocity potential function) etc. [9], [10].

According to [11], finite element methods could be used to model a piston. The methods are commonly used for thermal Analysis. A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component [12]. Due to the complicated working environment for the piston; on one hand, the FEA for the piston became more difficult; on the other hand, though there have been many methods which are put forward to apply optimal design, the optimal parameters are not easy to determine [4].

Since the main requirement of piston design is to measure the prediction of temperature distribution on the surface of piston which enable us to optimize the thermal aspect for the design at lower cost as reported by [3], this present study will focus on temperature distribution and heat transfer rate which are of much importance especially in spark ignition (SI) engines. This was achieved by formulating a model for analyzing the temperature distribution in an internal combustion engines piston as well as simulates the obtained results using COMSOL- Multiphysics.

2 METHODOLOGY

Combustion chamber temperature and the atmospheric temperature were the two parameters considered. These are required to study the temperature distributions as a function of time at different levels of such parameters. The tri-cycle engine shown in figure 1 was used for the experimental analysis. The engine was a 2-stroke, single cylinder spark Ignition engine, In-line, air- cooled type. The temperature measuring device used was thermocouple and the experimental aspect of the study was carried out on the test bed.

Fig. 2.1: The Tri-cycle used

Table 2.1: Prototype Piston Geometrical Information

1	Bore	80mm
2	Stroke	120mm

2.1 Analysis

COMSOL Multiphysics 4.3a software package which is a powerful finite element method (FEM) and partial differential equation (PDE) solution engine was used for the analysis. It has ten (10) add-on modules that expand the capabilities in the following application areas:

i. AC/DC Module
ii. Acoustics Module
iii. Chemical Species and Transport Module
iv. Electrochemistry
v. Fluid flow
vi. Heat transfer
vii. Plasma
viii. Radio Frequency (RF)
ix. Structural Mechanics
x. Mathematics

The heat transfer add-on module which has a temperature distribution in-built model was used for the simulation and analysis.

2.2 Temperature Distribution Analysis on the Model in COMSOL Multiphysics 4.3a

3-D model of piston was imported into the COMSOL Multiphysics for preprocessing. This consists of the following:

2.2.1 Selection of Physics

The problem studied was 3-D, transient and time dependent heat transfer problems.

2.2.2 Geometry

Figure 2.2 below shows the geometry of the piston (Material). The piston was designed using AutoCAD software and later converted to ipt model using Autodesk INVENTOR and the model was later imported into COMSOL Multiphysics via its Livelink for further analysis. In the engine, transfer of heat takes place due to difference in temperature from higher to lower temperature. Thus, there is heat transfer to the gases during intakes stroke and the first part of the compression stroke, but the during combustion and expansion processes the heat transfer take place from the gases to the walls [4].

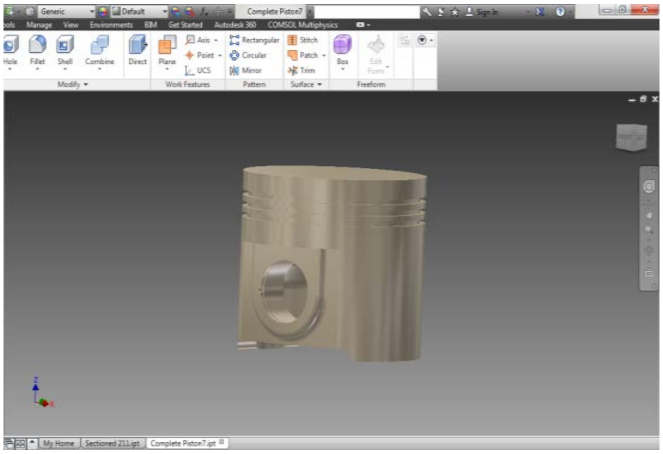

Fig. 2.2: Piston Model

2.2.3 Materials Selection and Properties

Aluminum alloys are widely used in engineering structures and components where light weight or corrosion resistance is required [3]. Aluminium alloy 6061 (UNS A96061), gasoline (petrol) and air were selected on the material browser and the values of the selected parameters were supplied into the material content.

Table 2.2: Material Contents of Air

Property	Name	Value	Units	Properties group
Ratio of specific heats	A	1.4	1	Basic
Heat capacity at constant pressure	c_p	1006	J/(kg*k)	Basic
Density	P	1290	Kg/m^3	Basic
Thermal conductivity	K	262	W/(m*k)	Basic
Dynamic Viscosity	M	0.00001697	Pa*s	Basic
Electrical Conductivity	σ	300	S/m	Basic
Speed of Sound	c	0.3	m/s	Basic

Table 2.3: Material Contents of Aluminium 6061 Alloy

Property	Name	Value	Units	Properties group
Dl	dL	5		Basic
CTE	CTE	2430		Basic
Thermal conductivity	K	167	W/(m*k)	Basic
Resistivity	Res	0.0000000399	Ω*m	Basic
Coefficient of thermal expansion	alpha	0.0234	1/k	Basic
Heat capacity at constant pressure	Cp	936		Basic
Mu	Mu	0.00000296		Basic
Electrical conductivity	sigma	45	s/m	Basic
Density	Rho	2700	Kg/m*3	Basic
Kappa	kappa	1		Basic
Ratio of specific heats	gamma	1.4	1	Basic

Table 2.4: Material Contents of Gasoline

Property	Name	Value	Units	Properties group
Dynamic Viscosity	Mu	0.0262	Pa*s	Basic
Heat capacity at constant pressure	Cp	1008	J/(kg*k)	Basic
Density	Rho	1050	Kg/m^3	Basic
Thermal conductivity	K	520	W/(m*k)	Basic

2.2.4 Parametric Studies (governing equations and boundary conditions)

The following boundary conditions were applied. Heat transfer co-efficient on the top and bottom surface, inflow heat flux on lateral surfaces and convective cooling.

A) Heat transfer in fluids (ht):

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \boldsymbol{U} \cdot \nabla \mathrm{T} = \nabla \cdot (\mathrm{K} \nabla \mathrm{T}) + \mathrm{Q} + \mathrm{Q_{vh}} + \mathrm{W_p} \quad (2.1)$$

B) Heat transfer in solids (ht):

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \boldsymbol{U} \cdot \nabla \mathrm{T} = \nabla \cdot (\mathrm{K} \nabla \mathrm{T}) + \mathrm{Q} \quad (2.2)$$

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C) Convective Cooling:

$$-n\cdot(-K\nabla T) = h\cdot(T_{ext} - T) \qquad (2.3)$$

Where the heat transfer coefficient h used is 1200 (w/m²*K) and the *external temperature* T_{ext} used is 293.15 K.

D) Thermal Insulation

The thermal insulation field was ignored, since the study interest was on temperature distribution.

E) Initial Values

The initial values of temperature T taken was 563.15 [K].

F) Inflow Heat Flux

The Inflow heat flux model for time dependent used is

$$-n\cdot(-K\nabla T) = -q_o(\boldsymbol{u}\cdot\boldsymbol{n})\frac{\int 1}{\int|\boldsymbol{u}.\boldsymbol{n}|} + \rho(\Delta h_{in} - \Delta h_{\infty})\,\boldsymbol{u}\cdot\boldsymbol{n} \quad (2.4)$$

$$\Delta h_{in} - \Delta h_{\infty} = \int_{T_\infty}^{T_{in}} C_p\,dT + \int_{P_\infty}^{PA}\frac{1}{\rho}\left(1+\frac{T}{\rho}\left(\frac{\partial\rho}{\partial T}\right)\Big|_P\right)dp \quad (2.5)$$

Where the Inward heat flux q_0 used is 2000 (W/m²) and the external temperature (T_{ext}) and pressure (P_{ext}) used are 293.15 K and 1 atm respectively.

2.2.5 Meshing

The mesh chosen was Free Tetrahedral. The Completed mesh consists of 86225 elements and the number of degrees of freedom solved for were 18553 in 367 s. (6 minutes, 7 seconds).

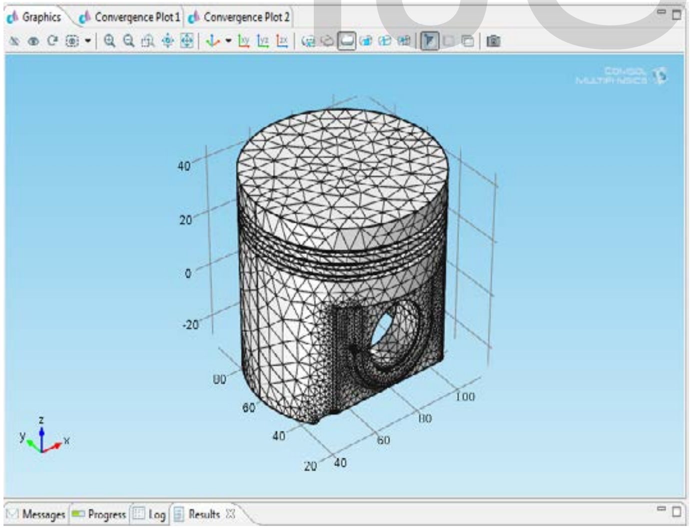

Fig. 2.3: Piston Mesh

2.2.6 Study:

In the Model Builder window, a time dependent study was chosen at a range of '0, 0.1, 10', in the edit field, before all temperatures (ht) plot were updated at a time discrete solver. The study was later computed for post processing and visualization.

2.3: Model-Post-processing and Visualization

In post processing mode different plots types were obtained from sets of selected parameters. The solution variables were later visualized using the post processing utilities for their derivatives, and the space coordinates. Many frequently used expressions were predefined as application mode variables, directly available from lists in the Plot Parameters.

3 RESULTS AND DISCUSSION

The obtained simulated results from the COMSOL Multiphysics are presented below:

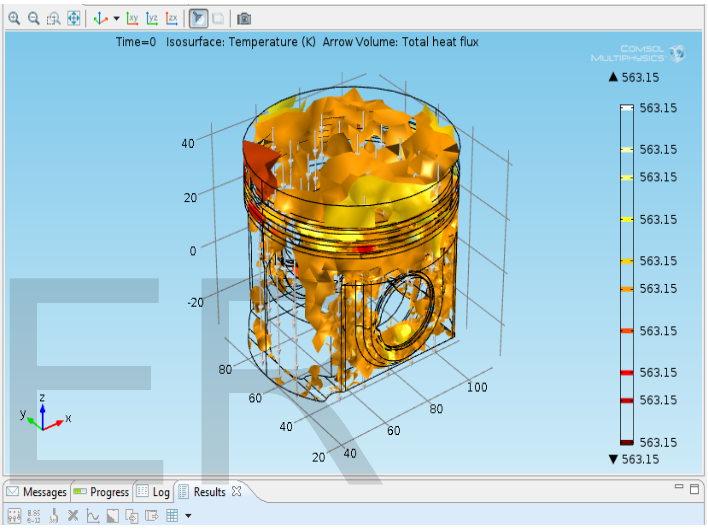
Time=0 Isosurface: Temperature (K) Arrow Volume: Total heat flux

Fig. 3.1: **Isosurface (Isotherma Contours) in 0 second**

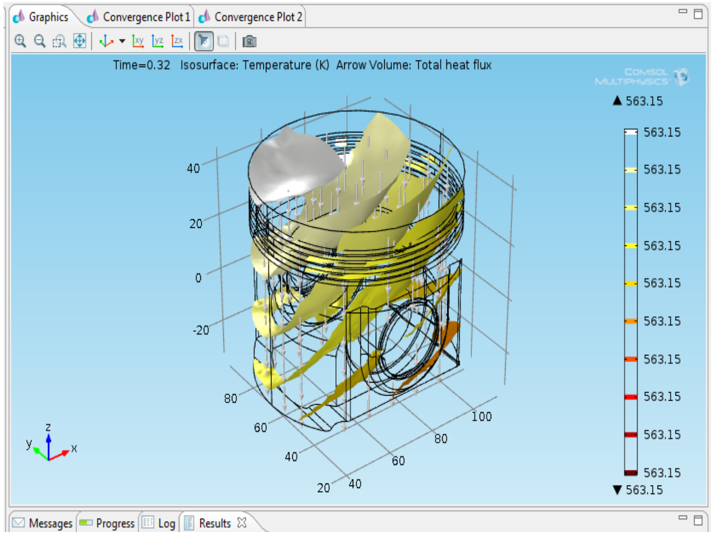
Time=0.32 Isosurface: Temperature (K) Arrow Volume: Total heat flux

Fig. 3.2: **Isosurface (Isotherma Contours) in 0.32 minutes**

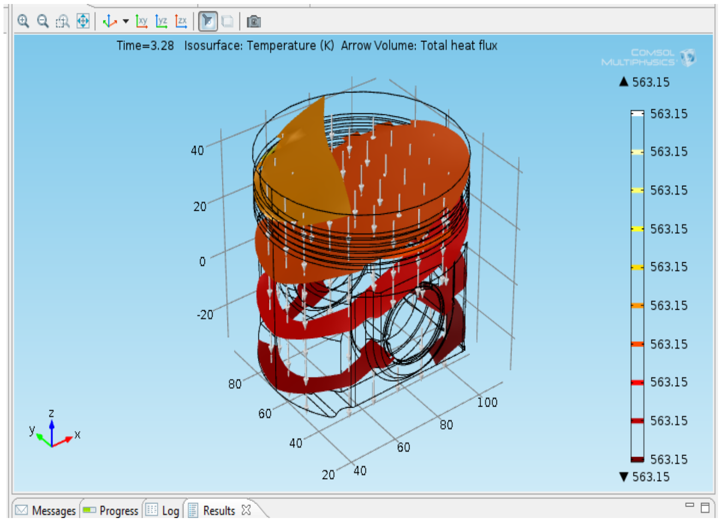

Fig. 3.3: **Isosurface (Isotherma Contours) in 3.28 minutes**

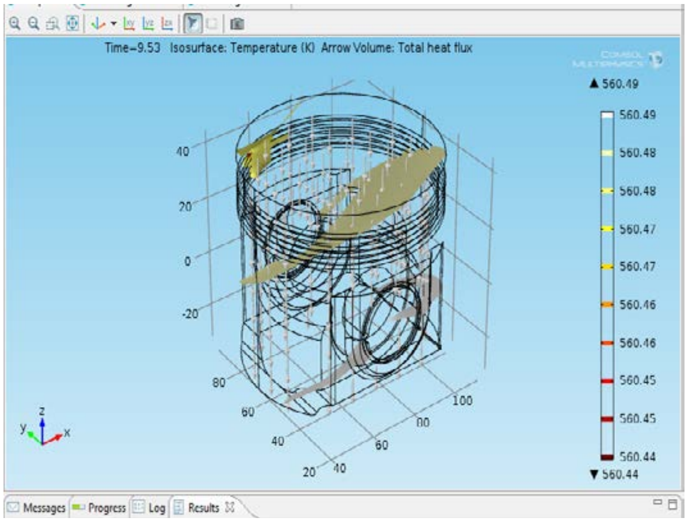

Fig. 3.6: **Isosurface (Isotherma Contours) in 9.53 minutes**

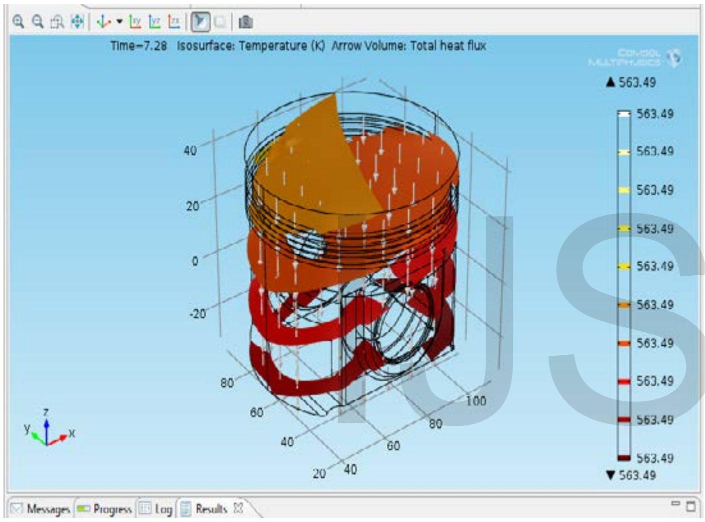

Fig. 3.4: **Isosurface (Isotherma Contours) in 7.28 minutes**

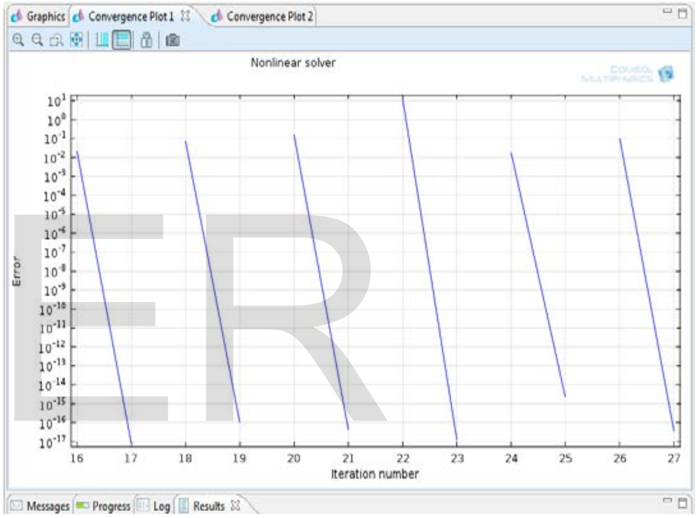

Figure 3.7: Non-Linear Solver

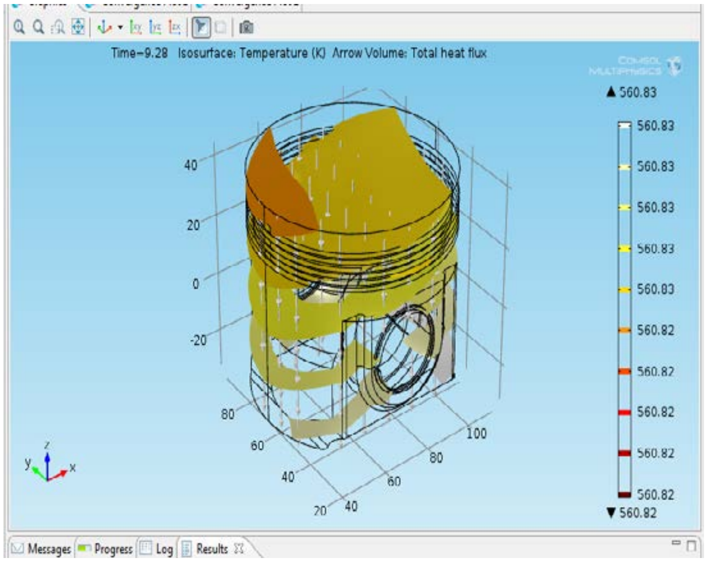

Fig. 3.5: **Isosurface (Isotherma Contours) in 9.28 minutes**

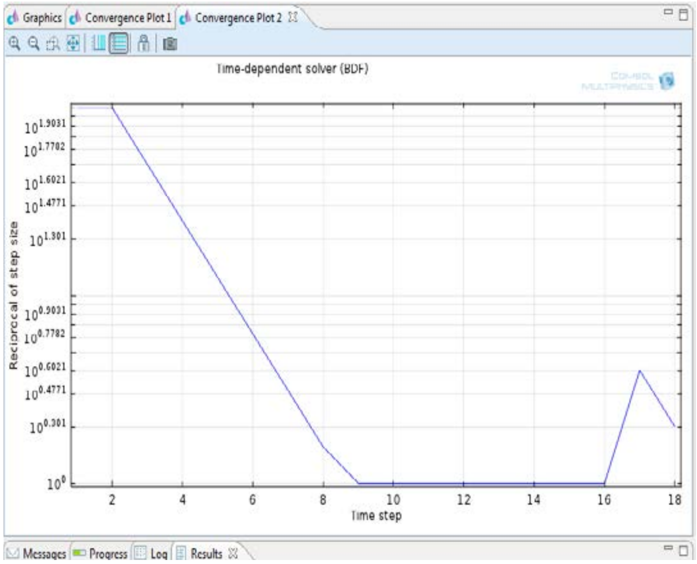

Figure 3.8: Time Dependent Solver

3.1: Discussion of Results

Fig. 3.1 shows the isosurface (isothermal contour) of the full piston model. At 0 second, the temperature distributions along the piston remain 563.15K.

Fig.3.2 shows the isosurface (isothermal contour) of the full piston model with the air-fuel mixture. The fuel has thouroghly mixed with air and the temperature of the piston is evenly distributed. Though, the temperature distributions at this time still remain 563.15K. This is an indication that there is no increament in the temperature after 0.32 minutes (19.2 seconds).

Fig.3.3 shows the isosurface (isothermal contour) of the full piston model in 3.28 minutes. At this point, the piston has become red hot which implies that it has undergone compression and is ready for the first power stroke to occur. Thus, the temperature distributions at this time still dwell on 563.15K.

Fig.3.4 shows the isosurface (isothermal contour) of the full piston model at TDC in 7.28 minutes. At this point, the hot air-fuel mixture is ignited by the spark plug. This is termed 'the power stroke'. Hence, the piston is superheated and this means that the temperature distribution of the piston has increased slightly to 563.49K.

From fig.3.5, the piston is returning to the bottom dead centre (BDC) thereby given room to heat transfer to take place in 9.28 minutes. It was also discovered from isosurface (isothermal contour) of the full piston model that the temperature distribution has reduced evenly to 560.83K which shows that, there is still trace of heat at the lower power of the piston. Hence, this implies that the temperature of the piston has reduced drastically after power stroke.

From fig.3.6, the piston has completely returned to the BDC thereby allow heat to be fully transfered in 9.53 minutes. It was discovered from isosurface (isothermal contour) of the full piston model that the temperature distribution has reduced to 560.44K. Also, a variation (560.49K to 560.44K) in temperature distribution could also be observed and there are no traces of unburnt gases at the end of first cycle of operation.

Fig.3.7 is the non-linear plot of the error against iteration number. The model was iterated in 27 times. The highest error of about $10^1$was observed when the result was on the 23rd iteration.

Fig. 3.8 shows the time dependent solver of the reciprocal of step size against time step. The highest reciprocal of step size was recorded when the time step was between 0 and 2. This indicates that heat is yet to be transferred for the first 2 seconds. Between the time step of 2 and 9, there was a gradual fall in the reciprocal of step size; this implies that heat transfer has taken place. Consequently, the piston returned from TDC to BDC. Between the step size of 9 and 16, the reciprocal of step size recorded the least constant value. This shows that the piston was at the BDC and heat has been completely transferred. At the same time, this is the period at which more air-fuel mixture comes in. Thus, another cycle of heat transfer occurred between 16 and 18 time-step. The first cycle recorded the highest reciprocal of step size, this supports the proposition that, the temperature of the piston head when the piston attains its first TDC is higher compared to the subsequent ones.

4 CONCLUSION AND RECOMMENDATION

The increased demand of automobile components is due to their improved performance and reduced costs. Piston as one of the automobile components should be designed in such a way that the temperature distribution on its surface to optimize the thermal aspect of the design at lower cost is predicted. Though, many of experimental studies regarding piston design only focused on the numerical studies like stress distribution, thermal and heat transfer analysis. A 3-D transient state temperature distribution analysis on a gasoline piston model of a tri-cycle has been critically worked on. Mathematical model was formulated, solved and simulated using a Finite Element Method (FEM) in-built in the COMSOL Multiphysics software 4.3a. It was discovered that the temperature in the combustion chamber of the tricycle engine varies with respect to time, along the piston. In conclusion, the transient analysis revealed that the temperature of the piston at TDC in the initial or first power stroke was higher compared to the subsequent power strokes. It implied that in the subsequent power strokes more heat were transferred due to some factors like surrounding air, oil etc which contributes to cooling effect. Thus, advancement in technology leads to this research, for improvement and longevity in two stroke engine performance. The results obtained can be compared using other available software packages like ANSYS, ABAQUS, NASTRAN, MATLAB, J-ANALYZER used in simulating the heat transfer on the piston of an IC Engines.

NOMENCLATURE

Cp	Heat capacity at constant pressure
ρ	Density
ϒ	(Gamma) Ratio of specific heat
α	Coefficient of thermal expansion
n	Number of iterations
u	Free stream velocity
k	Thermal conductivity
σ	(sigma) Electrical conductivity
μ	(mu) Absolute/Dynamic viscosity
C	Speed of sound
T	Temperature
t	Time (seconds)
h	Heat transfer coefficient
T_{ext}	External temperature
P_{ext}	External absolute pressure
q_0	Inward heat flux
Δh_{in}	Change in convective heat transfer coefficient at inlet

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